

## UNITED STATES PATENT APPLICATION

### METHOD FOR ACHIEVING IMPROVED SELECTIVITY IN AN ETCHING PROCESS

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## METHOD FOR ACHIEVING IMPROVED SELECTIVITY IN AN ETCHING PROCESS

### BACKGROUND OF THE INVENTION

This application is a continuation-in-part of U.S. patent application 09/427,841 to Patel et al. filed October 26, 1999 and U.S. patent application 09/649,569 to Patel et al., filed August 28, 2000, the contents of each being incorporated herein by reference.

This invention is in the area of the manufacture of MEMS (microelectromechanical systems) as well as semiconductor devices, or any other devices that require removal of a material relative to a substrate or other deposited material. In particular, this invention addresses gas-phase etching procedures, with particular emphasis on etching rate with a preferably spontaneous chemical etchant as well as detection of the end point in an etching process. The invention is also directed to apparatus useful for etching and detecting the end point of the etching reaction. "MEMS", "microelectromechanical" and "micromechanical" are used interchangeably throughout this application and each may or may not have an electrical component in addition to the microstructure component. The end point detected can be a point in an etch process where all of the material that is capable of reacting with the etchant gas has been removed and there is no more of the material remaining on the substrate or exposed to the etchant gas.

The use of etchants for removing sacrificial layers or regions in a multilayer structure without removal of an adjacent layer or region is a necessary and common step in the manufacture of semiconductor and MEMS devices. The MEMS devices of the present invention can be devices for inertial measurement, pressure sensing, thermal measurement, micro-fluidics, optics, and radio-frequency communications, with specific examples including optical switches, micromirror arrays for projection displays, accelerometers, variable capacitors and DC or RF switches. If a semiconductor device is etched, it can be any device that is made of or has on a substrate a material that is to be removed with a preferably gas phase chemical etchant.

The success of an etch step in the manufacture of microstructures is improved not only due to the selectivity of the etchant, but also due to the ability to accurately determine the end point of the etching process. Isotropic etching is of particular interest in processes where the purpose of the etch is to remove a sacrificial layer that is intervening between functional layers or between a functional layer and a substrate. Gas phase etchants, particularly in the absence of plasma, are desirable for isotropically removing a sacrificial layer.

Of potential relevance to certain embodiments of this invention is the prior art relating to particular etchant gases. Prominent among the etchants that are used for the removal of sacrificial

layers or regions in both isotropic and anisotropic etching procedures are noble gas fluorides and halogen fluorides. These materials, used in the gas phase, selectively etch silicon relative to other materials such as silicon-containing compounds, non-silicon elements, and compounds of non-silicon elements. Descriptions of how these materials are used in etching procedures appear in co-pending  
5 United States patent application serial no. 09/427,841 and 09/649,569 to Patel et al. and in portions of the present specification that follow.

The method of the present invention is useful for achieving high selectivity and/or detecting an end point in methods for producing semiconductor devices and deflectable MEMS elements (deflectable by electrostatic or other means) which, if coated (before or after gas phase processing) with a reflective  
10 layer, can act as an actuatable micromirror. Arrays of such micromirrors can be provided for direct view or projection display systems (e.g. projection television or computer monitors), as well as for optical switching. The present invention is also adaptable to detecting an end point in methods for etching microfabricated devices other than deflectable MEMS devices (e.g. semiconductor based devices, carbon nanotubes on glass, nondeflectable MEMS devices such as sensors, etc.)

## 15 SUMMARY OF THE INVENTION

The present invention provides improvements in the apparatus and methods used for the etching of layers or areas, and in particular, for achieving high selectivity and/or determining an end of the etching reaction. In one embodiment of the invention, a silicon material is etched at an etch rate of 27.7  
20  $\mu\text{m/hr}$  or less, and preferably at an etch rate of 7.2  $\mu\text{m/hr}$  or less. The method can also providing a sample to be etched in a chamber; providing a vapor phase etchant to the chamber to etch the sample, the vapor phase etchant capable of etching the sample in a non-energized state. The invention can also include monitoring the gas from the etching chamber; and determining the end point of the etch based on the monitoring of the gas from the etching chamber. Selectivity of the etch can further be improved by doping the silicon material.

## 25 BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram showing an example of a system for etching and stopping the etch in accordance with the present invention;

FIG. 2 is a diagram of a second example of a system for etching and stopping the etch in accordance with the present invention;

FIG. 3A is a side elevation view of one example of a reciprocating pump for use in one embodiment of the invention;

FIG. 3B is a pump flow diagram of the reciprocating pump of FIG. 3A together with associated flow lines and shutoff valves;

FIG. 4 is a process flow diagram for the apparatus of Fig. 2;

FIG. 5 is a graph of the partial pressure (ion current in a residual gas analyzer) of different etching products vs. time in the invention;

FIG. 6A is a graph of the partial pressure of SiF<sub>3</sub> vs. time;

FIG. 6B is a graph of the data of Fig. 6A back averaged over 40 previous data points;

FIG. 7A is a graph of the derivative taken from the data of Fig. 6B;

FIG. 7B is a graph of the data of Fig. 7A back averaged over 40 previous data points; and

FIG. 8 is a graph of the partial pressure (ion current in a residual gas analyzer) of different etching products vs. time in a prior art method and apparatus.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

While this invention is susceptible to a variety of constructions, arrangements, flow schemes, and embodiments in general, the novel features that characterize the invention are best understood by first reviewing a typical process flow arrangement in which the various aspects of this invention might be used.

As can be seen in Fig. 1, an apparatus is provided for etching a sample that includes a source chamber 11 containing a source of chemical etchant, maintained at a particular temperature and pressure for maintaining the etchant source in a solid or liquid state (e.g. solid state for XeF<sub>2</sub> crystals, liquid state for BrF<sub>3</sub>, etc.). An expansion chamber 12 is in fluid communication with source chamber 11 and has any suitable size (e.g. a volumetric capacity of 29 cubic inches (0.46 liter)) to receive etchant gas from the source chamber 11, with a shutoff valve 13 joining these two chambers. An etch chamber 14 is provided in fluid communication with expansion chamber 12 and has any suitable size (e.g. volumetric capacity of 12 cubic inches (0.18 liter)) to contain the sample microstructure to be etched. It is preferred that the etch chamber be smaller than the expansion chamber. The etch chamber 14 is connected to the expansion chamber 12 via a shutoff valve 15. Also included in the apparatus is a first gas source 16 in fluid communication with the expansion chamber 12 via a further shutoff valve 17, a second gas source 18 in fluid communication with the expansion chamber through a separate shutoff valve 19, a vacuum pump 21 and associated shutoff valves 22, 23 to control the evacuation of the chambers.

Also shown in Fig. 1 are a third gas source 24 serving as a pump ballast with an associated shutoff valve 25 to prevent backstreaming from the pump 21, and needle valves 26, 27, 28 to set the gas flow rates through the various lines and to permit fine adjustments to the pressures in the chambers. Also shown, as will be discussed in more depth below, are gas analyzer 1 and valves 3 and 5 on opposite sides of the analyzer. The expansion chamber 12 and the etch chamber 14 can both be maintained at a particular temperature, while different gases are placed in the first and second gas sources for the various etching processes. It should be noted that a single gas source could be used in place of gas sources 16 and 18.

The general procedure followed in these experiments began with the evacuation of both the expansion chamber 12 and the etch chamber 14, followed by venting both chambers to atmospheric pressure with gas from the first gas source 16 by opening the two shutoff valves 17, 15, between this gas source and the two chambers. The sample was then placed in the etch chamber 14 (with the shutoff valves 7, 15 open during the sample insertion) which was then sealed, and both the expansion chamber 12 and the etch chamber 14 were evacuated. All valves were then closed.

The connecting valve 15 between the expansion chamber 12 and the etch chamber 14 was opened, and the shutoff valve 17 at the outlet of the first gas source 16 was opened briefly to allow the gas from the first gas source to enter the expansion and etch chambers. The shutoff valve 17 is then closed. The connecting valve 15 is then closed, and the expansion chamber 12 is evacuated and isolated. The supply valve 13 from the etchant source chamber 11 is then opened to allow etchant gas to enter the expansion chamber (due to the higher temperature of the expansion chamber). The supply valve 13 is then closed, outlet valve 23 is opened, and the needle valve 27 is opened slightly to lower the etchant pressure in the expansion. Both the outlet valve 23 and the needle valve 27 are then closed. The shutoff valve 19 at the second gas source 18 is then opened and with the assistance of the needle valve 26, gas from the second gas source is bled into the expansion. At this point the expansion chamber 12 contains the etchant gas plus gas from the second gas source 18, while the etch chamber 14 contains gas from the first gas source.

With pump 21 on, the connecting valve 15 between the expansion chamber 12 and the etch chamber 14 is then opened, and valves 3 and 5 are opened on both sides of gas analyzer 1, to allow the gas mixture from the expansion chamber to enter the etch chamber and flow through the etch chamber and gas analyzer, thereby beginning the etch process. As will be discussed further below, the etch process is continued until an end point is detected via the gas analyzer.

Many alternatives to the process scheme described above can be used. Additional gas sources and chambers, for example, can be utilized. For example, depending upon the diluent(s) used (gas

sources 16 and 18), a plurality of diluent sources (N<sub>2</sub>, Ar, He, etc.) can be connected to the expansion chamber and/or to the recirculation loop for bleeding the system after an etch. The air distribution system within the etching chamber can also be varied, for example by including U-shaped or cone-shaped baffles, or by using additional perforated plates and/or baffles.

A specific alternative to the embodiment of Fig. 1 is illustrated in Fig. 2. FIG. 2 represents such a process flow arrangement in which the process is an etching process having a detectable end point. The etchant gas originates in a source chamber 11. An example of an etchant gas that is conveniently evaporated from a liquid is bromine trifluoride, whereas an example of an etchant gas that is conveniently sublimated from solid crystals is xenon difluoride. Effective results can be achieved by maintaining the crystals under 40 degrees C (e.g. at a temperature of 28.5°C). (Xenon difluoride is only one of several etchant gases that can be used. Examples of other gases are presented below.) The sublimation pressure of xenon difluoride crystals at 28.5°C is 5-11 mbar (4-8 torr). An expansion chamber 12 receives xenon difluoride gas from the crystals in the source chamber(s) 11, and a shutoff valve 13 is positioned between the source and expansion chambers. The sample 14 to be etched is placed in an etch chamber 15 (which contains a baffle 16 a perforated plate 17), and a reciprocating pump 18 that is positioned between the expansion chamber 12 and the etch chamber 15. (The reciprocating pump and its valves are shown in more detail in a FIGS. 3a and 3b and described below.) Also illustrated in Fig. 2, and will be discussed further below, is a gas analyzer 1 with valves 3 and 5 that control the flow of gas from the etching chamber through the gas analyzer.

Also shown are two individual gas sources 19, 20 supplying the expansion chamber 12 through shutoff valves 21, 22, a vacuum pump 23 and associated shutoff valves 24, 25, 26, 27, 28 to control the evacuation of the chambers, a third gas source 29 serving as a pump ballast with an associated shutoff valve 30 to prevent backstreaming from the pump 23, and manually operated needle valves 31, 32, 33, 34, 35, 83 to set the gas flow rates through the various lines and to permit fine adjustments to the pressures in the chambers. When xenon difluoride is used, the expansion chamber 12 and the etch chamber 15 are typically maintained at around room temperature (e.g. 25.0°C). However, the expansion chamber and etch chamber could also be heated (e.g. to between 25 and 40 degrees C), though this would likely be performed in conjunction with directly cooling the sample being processed, as will be discussed below. A recirculation line 36 permits gas to flow continuously through the etch chamber 15 in a circulation loop that communicates (via valves 26, 27, and 34, 35) with the expansion chamber 12 and reenters the etch chamber 15 by way of the reciprocating pump 18. Valve 85 permits gas transfer between expansion chamber 12 and etch chamber 15 via a portion of the recirculation line 36 without traversing recirculation pump 18. Valve 86 in path 40 permits introduction of etchant gas into

the expansion chamber 12 to replenish the etchant mixture during the etching process. The valves are preferably corrosive gas resistant bellows-sealed valves, preferably of aluminum or stainless steel with corrosive resistant O-rings for all seals (e.g. Kalrez <sup>™</sup> or Chemraz <sup>™</sup>). The needle valves are also preferably corrosion resistant, and preferably all stainless steel. As an optional feature, a filter 39 can be placed in the recirculation line 36 to remove etch byproducts from the recirculation flow, thereby reducing the degree of dilution of the etchant gas in the flow. The filter can also serve to reduce the volume of effluents from the process.

The etch chamber 15 can be of any shape or dimensions, but the most favorable results will be achieved when the internal dimensions and shape of the chamber are those that will promote even and steady flow with no vortices or dead volumes in the chamber interior. A preferred configuration for the etch chamber is a circular or shallow cylindrical chamber, with a process gas inlet port at the center of the top of the chamber, plus a support in the center of the chamber near the bottom for the sample, and an exit port in the bottom wall or in a side wall below the sample support. The baffle 16 is placed directly below the entry port. The distance from the port to the upper surface of the baffle is not critical to this invention and may vary, although in preferred embodiments of the invention the distance is within the range of from about 0.1 cm to about 6.0 cm, and most preferably from about 0.5 cm to about 3.0 cm. Although its shape is not shown in Fig. 2, the baffle is preferably circular or otherwise shaped to deflect the gas stream radially over a 360° range. The perforated plate 17 is wider than the baffle 16 and preferably transmits all gas flow towards the sample. A preferred configuration for the perforated plate is one that matches the geometry of the sample; thus, for a circular sample the perforated plate is preferably circular as well.

FIGS. 3a and 3b are diagrams of an example of a reciprocating pump 18 that can be used in the practice of this invention. The design shown in these diagrams can be varied in numerous ways, such as by increasing the number of chambers to three or more, or by arranging a series of such pumps in parallel. The following discussion is directed to the particular design shown in these diagrams.

The side elevation view of FIG. 3a shows the pump housing 41, which consists of two stationary end walls 42, 43 joined by bellows-type side walls 44, 45. The bellows-type side walls 44, 45 are so-called because they are either pleated like an accordion or otherwise constructed to permit bellows-type expansion and contraction. The end walls 42, 43 and the bellows-type sidewalls 44, 45 together fully enclose the interior of the pump except for inlet/outlet ports on each side wall. The arrangement of these ports is shown in the pump flow diagram of FIG. 3b, the left side-wall 42 having one inlet/outlet port 46, and the right side wall 43 likewise having one inlet/outlet port 48. Remotely controlled shutoff

valves 51, 52, 53, 54 are placed on the external lines leading to or from each inlet/outlet port. For fail-safe operation, shutoff valves 51, 54 are normally open and shutoff valves 52, 53 are normally closed.

The movable partition 60 shown in FIG. 3a divides the pump interior into two chambers 61, 62, the partition and its connections to the remaining portions of the housing being fluid-impermeable so that the two chambers are completely separate with no fluid communication between them. The partition 60 joins the bellows-type side walls 44, 45 and moves in the two directions indicated by the two-headed arrow 63. The movement is driven by a suitable drive mechanism (not shown) capable of reciprocating movement. Many such drive mechanisms are known to those skilled in the art and can be used. In the view shown in FIG. 3a, movement of the partition to the left causes the left chamber 61 to contract and the right chamber 62 to expand. With the pump shutoff valves appropriately positioned, i.e., valves 52 and 53 open and valves 51 and 54 closed, the contracting left chamber 61 will discharge its contents through its inlet/outlet port 46 while the expanding right chamber 62 will draw gas in through its inlet/outlet port 48. Once the partition 60 has reached the end of its leftward travel, it changes direction and travels to the right and the shutoff valves are switched appropriately, causing the expanded right chamber 62 to contract and discharge its contents through its inlet/outlet port 48 while the contracted left chamber 61 expands and draws fresh gas in through its inlet/outlet port 46. In this manner, the pump as a whole produces a gas flow in a substantially continuous manner, the discharge coming alternately from the two chambers. A controller 64 governs the direction and range of motion, and the speed and cycle time of the partition 60, and coordinates the partition movement with the opening and closing of the shutoff valves 51, 52, 53, 54. Conventional controller circuitry and components can be used.

The pump for recirculating the process gas as shown, and others within the scope of this invention, has no sliding or abrading parts or lubricant that come into contact with the process gas. Alternative pumps that meet this criteria are possible, including pumps with expandable balloon chambers, pumps with concentric pistons connected by an elastic sealing gasket, or peristaltic pumps. The pump materials, including the bellows-type walls, can thus be made of materials that are resistant or impervious to corrosion from the etchant gas. One example of such a material, useful for operating temperatures below 50°C, is stainless steel. Others are aluminum, Inconel, and Monel. Still others will be readily apparent to those experienced in handling these gases. While the capacity and dimensions of the pump and its chambers may vary, a presently preferred embodiment is one in which the change in volume of each chamber upon the movement of the partition across its full range is approximately from .05 to 4.2 L, though preferably from .1 to 1.5 L, with one example being 0.5 L. Larger chamber sizes (e.g. 5 to 20 L) are possible, which, if combined with a slower pumping speed, can benefit from



lower wear on the pump. At a partition speed of one cycle every two seconds, the pump rate (for 0.5 L) will be 30 L/min. Different combinations of pump sizes and pump speeds are possible, though the preferred pump volume per time is between 7 and 150 L/min, with a preferred range of from 30 to 90 L/min.

5 The pump described above can be lined with a suitable lining to further reduce particulate contamination of the process gas mixture during etching. Pumps that are not of the bellows type can also be used. The preferred pumps are those that are resistant to corrosion by the process gas mixture and those that are designed to avoid introducing particulate or liquid material into the process gas mixture. Dry pumps, i.e., those that do not add exogenous purge or ballast gas into the process gas  
10 mixture, are preferred. Alternatively, the process gas could be circulated by temperature cycling (with large variations in the heating and cooling of the recirculation path).

The following is a generalized description of the etching process and its chemical parameters in relation to Fig. 2. This description is included to show the context in which the features described above are most likely to be used.

15 The apparatus and methods of this invention can be used in etching processes that are known in the art and in the literature. These processes include the use of dry-etch gases in general, including  $\text{Cl}_2$ ,  $\text{HBr}$ ,  $\text{HF}$ ,  $\text{CCl}_2\text{F}_2$  and others. Preferred etchant gases, particularly for etching silicon, are gaseous halides (e.g. fluorides) such as noble gas fluorides, gaseous halogen fluorides, or combinations of gases within these groups (again, preferably without energizing the gas, other than heating to cause  
20 vaporization or sublimation). The noble gases are helium, neon, argon, krypton, xenon and radon, and among these the preferred fluorides are fluorides of krypton and xenon, with xenon fluorides the most preferred. Common fluorides of these elements are krypton difluoride, xenon difluoride, xenon tetrafluoride, and xenon hexafluoride. The most commonly used noble gas fluoride in silicon etch procedures is xenon difluoride. Halogen fluorides include bromine fluoride, bromine trifluoride, bromine  
25 pentafluoride, chlorine fluoride, chlorine trifluoride, chlorine pentafluoride, iodine pentafluoride and iodine heptafluoride. Preferred among these are bromine trifluoride, bromine trichloride, and iodine pentafluoride, with bromine trifluoride and chlorine trifluoride the more preferred. Combinations of bromine trifluoride and xenon difluoride are also of interest. The etch process is generally performed at a pressure below atmospheric. It is preferred that the etchants described herein be used in the gaseous  
30 state (e.g. non-plasma) or otherwise in the absence of added energy (except heat to aid sublimation or vaporization of the starting etchant gas or liquid), and in the absence of electric fields, UV light or other electromagnetic energy, or other added fields or energy sources which would energize the etchant gas beyond its normal energy as a gas at a particular temperature.

The etch preferably utilizes an etchant gas capable of spontaneous chemical etching of the sacrificial material at room temperature, preferably isotropic etching that chemically (and not physically) removes the sacrificial material. In a preferred embodiment, the etchant is capable at room temperature of reacting with the sacrificial material and where the reaction product(s) is a gaseous component that is released from the sacrificial material surface due to being in a gaseous state. No UV or visible light or other electromagnetic radiation or electric fields are needed, or any energy that would energize the gas molecules to physically bombard and physically remove the sacrificial material. Though the etch could be performed with the application of heat or the presence of light from the room surrounding the etch chamber, the etchant is capable of spontaneously etching the sacrificial material at room temperature without any applied heat, visible, UV or other electromagnetic radiation, ultrasonic energy, electric or magnetic fields, etc. The etchant is preferably not broken down into atoms, radicals and/or ions by an rf glow discharge, the etchant is transported by diffusion to the surface of the material being etched (in addition to pumping – e.g. by recirculating the etchant repeatedly through the etching chamber), the etchant is adsorbed on the surface, a chemical reaction occurs between the etchant and the material being etched with the formation of a volatile product, and the product is desorbed from the surface and diffuses into the bulk of the gas and eventually exits the etching chamber. The apparatus, therefore, can be without a source of RF or microwave energy, though it is possible to run the process of the invention in a plasma apparatus without energizing the etchant to form a plasma.

Taking as an example  $\text{BrCl}_3$ , a molecule of  $\text{BrCl}_3$  could hypothetically be placed next to a silicon molecule bound to other silicon molecules in crystalline silicon, polysilicon or in an amorphous silicon matrix. The bond energies of the Cl atoms to the Br atoms are sufficiently weak, and the bond energy of the silicon atom to other silicon atoms is sufficiently weak, and the attraction forces between Si and Cl are sufficiently strong, that without a physical bombardment of the  $\text{BrCl}_3$  on the silicon, Cl will disassociate from Br and bond to Si to form various products such as  $\text{SiCl}$ ,  $\text{SiCl}_2$ ,  $\text{SiCl}_3$ ,  $\text{SiCl}_4$ , etc., which etch products are a gas at room temperature and dissipate from the silicon surface, thus removing sacrificial silicon material. The same process occurs with  $\text{XeF}_2$ ,  $\text{BrF}_3$  and the other vapor phase spontaneous chemical etchants.

Such chemical etching and apparatus for performing such chemical etching are disclosed in US patent application 09/427,841 to Patel et al. filed October 26, 1999, in US patent application 09/649,569 to Patel et al. filed August 28, 2000, mentioned previously, and in US patent application 60/293,092 to Patel et al. filed May 22, 2001 incorporated herein by reference. Preferred etchants for the etch are gas phase fluoride etchants that, except for the optional application of temperature, are not energized. Examples include gaseous acid etchants ( $\text{HF}$ ,  $\text{HCl}$ ,  $\text{HI}$  etc.), noble gas halides such as  $\text{XeF}_2$ ,  $\text{XeF}_6$ ,

KrF<sub>2</sub>, KrF<sub>4</sub> and KrF<sub>6</sub>, and interhalogens such as IF<sub>5</sub>, BrCl<sub>3</sub>, BrF<sub>3</sub>, IF<sub>7</sub> and ClF<sub>3</sub>. It is also possible to use fluorine gas, though handling of fluorine gas makes this a less desirable option. The etch may comprise additional gas components such as N<sub>2</sub> or an inert gas (Ar, Xe, He, etc.). In the etching process, except for optional heating, the gas is not energized and chemically etches the sacrificial material isotropically. In this way, the sacrificial material is removed and the micromechanical structure is released. In one aspect of such an embodiment, BrF<sub>3</sub> or XeF<sub>2</sub> are provided in a chamber with diluent (e.g. N<sub>2</sub> and He). An initial plasma etch, preferably in a separate etching apparatus, can be performed prior to etching as set forth above. This sequential etch is set forth further in 60/293,092 to Patel et al. filed May 22, 2001, the subject matter of which is incorporated herein by reference.

While the source chamber 11 can be a single chamber, the arrangement shown in FIG. 4 is an optional one in which the source chamber is actually a pair of chambers 11a and 11b arranged in series. The first of these chambers 11a contains the source material primarily in its condensed form, i.e., either as crystals to be sublimated or liquid to be vaporized. The second chamber 11b receives the source material gas evolved by sublimation from the crystals or by vaporization from the liquid in the first chamber 11a. To maintain these phases, the two chambers 11a and 11b will preferably be maintained at different temperatures (preferably at least 5 degrees C difference), the former 11a at the lower temperature to keep the material in its condensed form (solid crystals or liquid) and the latter 11b at the higher temperature (and possibly a higher pressure as well) to keep the material in the vapor form (and to avoid the problem of condensation) at a pressure sufficiently high to allow it to be supplied to the succeeding chambers at the pressures needed in those chambers. In one embodiment, the two chambers are held at temperatures above room temperature, with chamber 11b held at a temperature from 2 to 24 degrees C (preferably around 5 to 10 degrees C) higher than the temperature of chamber 11a. Such a two-chamber embodiment could likewise be utilized in a system such as that illustrated in Fig. 1. Chambers 11a and 11b could also be arranged in parallel. Also shown in Fig. 4 are the expansion chamber 12, the etching chamber 15, and pumps 18 and 23.

The terms "sample" and "microstructure" are used herein to denote the article from which a material is sought to be removed or to which a material is to be added, whether the material forms a layer among a plurality of layers, layers among a plurality of layers or a region adjacent to other regions in the same plane. The "sample" may thus be a single mirror element and its associated layers of other materials, a test pattern, a die, a device, a wafer, a portion of a wafer, or any article from which a portion is to be removed or added. The invention is particularly suitable for processes where the size of the portion of material that is being added or removed is less than 5mm in at least one of its dimensions, preferably less than 1mm, more preferably less than 500 $\mu$ m, and most preferably less than 100 $\mu$ m.

The invention is also well suited to adding or removing material (e.g., in the form of holes or layers) in a submicron environment (e.g. in the range of 10nm to less than 1000nm) (as sometimes needed, for example, in MEMS and MOEMS).

In the system depicted in the drawings, as well as other systems within the scope of this invention, a single charge of etchant can be placed in the source chamber or the expansion chamber, then released (with or without diluents) into the recirculation loop. Additional etchant can be introduced to replenish the circulating stream as the amount of etchant in the recirculation loop decreases over time. Other variations of the process will be apparent to those skilled in the art.

When the material to be removed by etching is silicon, certain etching processes supply the etchant gas as a mixture of gases of which one component is the etchant gas itself (or a mixture of etchant gases) while other components are non-etchant diluents. Whether the gas consists entirely of etchant gas(es) or contains non-etchant components as well, the rate of the etch reaction may vary with the partial pressure of the etchant gas. The partial pressure may vary, but in most applications, particularly those in which silicon is being etched, best results will be obtained with the etchant gas at a partial pressure of at least about 0.1 mbar (0.075 torr), preferably at least about 0.3 mbar (0.225 torr), more preferably within the range of from about 0.3 mbar (0.225 torr) to about 30 mbar (22.5 torr), and most preferably from about 1 mbar (0.75 torr) to about 15 mbar (11.25 torr). These pressure ranges are particularly applicable to xenon difluoride etching.

In certain processes, non-etchant gas additive(s) are included to increase the selectivity of the silicon etch. Preferred additives for this purpose are non-halogen-containing gases. A single such additive or a mixture of such additives can be used. In preferred embodiments of this invention, the additives are those whose molar-averaged formula weight (expressed in daltons or grams per mole) is less than the formula weight of molecular nitrogen, preferably about 25 or less, still more preferably within the range of from about 4 to about 25, still more preferably within the range of from about 4 to about 20, and most preferably within the range of from about 4 to about 10. If a single additive species is used, the "molar-averaged formula weight" is the actual formula weight of that species, whereas if two or more additive species are used in the same gas mixture, the molar-averaged formula weight is the average of the formula weights of each species in the mixture (exclusive of the noble gas fluoride) calculated on the basis of the relative molar amounts (approximately equal to the partial pressures) of each species. In terms of thermal conductivity, preferred additives are those whose thermal conductivity at 300 K (26.9°C) and atmospheric pressure ranges from about 10 mW/(m K) (i.e., milliwatts per meter per degree Kelvin) to about 200 mW/(m K), and most preferably from about 140 mW/(m K) to about 190 mW/(m K). In general, the higher the thermal conductivity of the additive, the greater the

improvement in selectivity. Examples of additives suitable for use in this invention are nitrogen (N<sub>2</sub>, thermal conductivity at 300 K: 26 mW/(m K)), argon (Ar, thermal conductivity at 300 K: 18 mW/(m K)), helium (He, thermal conductivity at 300 K: 160 mW/(m K)), neon (Ne, thermal conductivity at 300 K: 50 mW/(m K)), and mixtures of two or more of these gases. Preferred additive gases are helium, neon, mixtures of helium and neon, or mixtures of one or both of these with one or more non-etchant gases of higher formula weight such as nitrogen and argon. Particularly preferred additives are helium and mixtures of helium with either nitrogen or argon.

The degree of selectivity improvement may vary with molar ratio of the additive to the etchant gas. Here again, the molar ratio is approximately equal to the ratio of the partial pressures, and in this case the term "molar ratio" denotes the ratio of the total number of moles of the additive gas (which may be more than one species) divided by the total number of moles of the etchant gas (which may also be more than one species). In most cases, best results will be obtained with a molar ratio of additive to etchant that is less than about 500:1, preferably within the range of from about 1:1 to about 500:1, preferably from about 10:1 to about 200:1, and most preferably from about 20:1 to about 150:1. In one example, the ratio is set at 125:1.

The temperature at which the etch process is conducted can likewise vary, although the partial pressure of the etchant gas will vary with temperature. The optimal temperature may depend on the choice of etchant gas, gaseous additive or both. In general, and particularly for procedures using xenon difluoride as the etchant gas, suitable temperatures will range from about -60°C to about 120°C, preferably from about -20°C to about 80°C, and most preferably from about 0°C to about 60°C. For xenon difluoride, the silicon etch rate is inversely proportional to the temperature over the range of -230°C to 60°C. The improvement in selectivity can thus be further increased by lowering the etch process temperature.

The flow parameters will be selected such that the time during which the sample will be exposed to the etchant gas will be sufficient to remove all or substantially all of the silicon. The expression "substantially all of the silicon" is used herein to denote any amount sufficient to permit the finished product to function essentially as effectively as if all of the silicon had been removed. An example of the structures to which this invention will be applied is that depicted in United States Patent No. 5,835,256, incorporated herein by reference, in which a silicon nitride layer is deposited over a polysilicon layer, and the silicon nitride layer is patterned to leave vias that define the lateral edges of the mirror elements. Access to the sacrificial polysilicon layer is through the vias, and the etching process removes the polysilicon below the vias by etching in the vertical direction (i.e., normal to the planes of the layers) while also removing the polysilicon underneath the silicon nitride by etching in the

lateral direction (parallel to the planes of the layers). The process is also effective for etching silicon relative to multiple non-silicon layers. Also, it should be noted that the silicon can contain impurities, and in particular may contain a large amount of hydrogen (e.g. up to 25 at% or more) depending upon the deposition method used.

The process design shown in FIG. 2 is but one of many designs in which good selectivity and/or end point detection in accordance with the present invention can be achieved. The FIG. 2 design itself can be used with many different combinations and sequences of valve openings and closings. One such sequence is as follows:

1. Solid or liquid etchant material (such as  $\text{XeF}_2$ ) is placed in the source chamber(s) 11.
2. A sample 14 is placed in the etch chamber 15.
3. The expansion chamber 12 and the etch chamber 15 are each evacuated.
4. The expansion chamber 12 and the etch chamber 15 are preconditioned by a) flooding one or both of the chambers with an inert gas (such as  $\text{N}_2$ , for example), b) implementing a temperature ramp (e.g. consisting of raising the temperature of one or both of the chambers for fixed time followed by cooling the temperature of one or both chambers after step 5 and finishing with raising the temperature of one or both chambers after step 15), or c) both flooding and implementing temperature ramp. The sample temperature can be ramped to match or differ from than the chamber temperature ramp.
5. Both the expansion chamber 12 and the etch chamber 15 are then evacuated.
6. The expansion chamber 12 and the etch chamber 15 are then filled with one or more diluents from the individual gas sources 19, 20.
7. The expansion chamber 12 is then evacuated.
8. The expansion chamber 12 is then filled with  $\text{XeF}_2$  gas from the source chamber(s) 11 (generated by sublimation from the  $\text{XeF}_2$  crystals in the source chamber).
9.  $\text{XeF}_2$  gas is then pumped out of the expansion chamber 12 by the vacuum pump 23 to lower the  $\text{XeF}_2$  gas pressure in the expansion chamber to the desired  $\text{XeF}_2$  process pressure to be used for etching the sample.
10. One or more diluent gases from the gas sources 19, 20 are then added to the expansion chamber 12.
11. All valves are then closed except the manual needle valves.
12. The recirculation pump 18 is then activated to start a flow of diluent gas through the etch chamber 15. Also valves 3 and 5 are opened to allow part of the recirculating gas to flow through the gas analyzer.

13. The shutoff valves 26, 27 on the XeF<sub>2</sub> recirculation loop are then opened to cause XeF<sub>2</sub> gas to enter the recirculation loop 36.
14. Recirculation of the XeF<sub>2</sub> gas through the etch chamber is continued until an end point to the etch is determined via the gas analyzer.
- 5 15. Both the expansion chamber 12 and the etch chamber 15 are then evacuated.
16. The expansion chamber 12 and the etch chamber 15 are post-conditioned by a) flooding one or both of the chambers with an inert gas, b) increasing the temperature of one or both of the chambers, c) pumping out one or both of the chambers, or d) following a time ordered sequence of one or more of flooding/heating/evacuating.
- 10 17. The finished sample is then removed from the etch chamber.

This procedure can be varied without detriment to the product quality. Steps 12 and 13, for example, can be performed in reverse order. Other variations will be apparent to those skilled in the art.

#### Example:

For etching a 6" glass substrate with MEMS devices, typical apparatus and process parameters include: double source chamber design with 11a at 28 C, 11b at 31 C and intermediate connector piece at 35 C. Expansion chamber 12 and etch chamber 15 at 23 C. In step 6 above, both chambers 12 and 15 are filled with a mixture of 45 T Nitrogen (N<sub>2</sub>) and 450 T Helium (He); total gas pressure is 495 T. In step 8, the chamber 12 is filled with XeF<sub>2</sub> gas above 4.2 T. In step 9, the XeF<sub>2</sub> gas in chamber 12 is reduced to 4 T for use in the process. In step 10, chamber 12 receives 47 T of Nitrogen (N<sub>2</sub>) and 470 T of Helium (He); total gas pressure in chamber 12 at the end of step 10 is 521 T.

#### END POINT DETECTION:

As can be seen in Toda R., Minami K., and Esashi M., "Thin Beam Bulk Micromachining Based on RIE and Xenon Difluoride Silicon Etching", Transducers '97, IEEE, pp.671-3, Fourier Transform spectroscopy is used to monitor the etching of silicon by xenon difluoride. The process is run in pulse mode where the etchant gas enters the etching chamber at the beginning of the etch, and the etching chamber is evacuated only at the end of the etch. There is a slow build up of SiF<sub>4</sub> in the chamber which gradually forms a plateau as the etch nears completion. With such an arrangement it is very difficult to determine where along the plateau is the proper end point. As stated in the reference, it is considered that the reaction between XeF<sub>2</sub> and silicon is mostly finished within 30 seconds after the SiF<sub>4</sub> absorption peak is nearly saturated. Attempting to pinpoint an end point on the plateau of the curve of SiF<sub>4</sub> is more of a guess than an actual calculated end point determination.

Another XeF<sub>2</sub> etching method is a flow through system where an unimpeded gas flows out of the etching chamber at substantially the same rate as etchant flows into the etching chamber. Such a system is disclosed in EP 0878824 to Surface Technology Systems. If a gas analyzer were to be placed at or downstream from the etching chamber for analyzing etching products from the etching reaction, due to a lack of impeding the gas flow out of the etching chamber in accordance with the invention, only noise would be detected by such a hypothetical arrangement (see Fig. 9).

In accordance with the present invention, whether the etch system is a flow through continuous (or at least partially continuous) system, or a recirculation etch system, a gas analyzer is provided that is capable of accurately detecting an end point of the etching reaction. Whether the gas flow is recirculated or vented to ambient, it is desirable that the gas flow into the etching chamber be impeded. The impedance can be any impedance as long as it is greater than 0 (as in the flow through system mentioned above) and less than infinite (as in the pulse system mentioned above). The flow can be continuous or partially continuous (stop-start), though a pure pulse mode is not desirable for detecting end point in accordance with the invention).

The gas analyzer can be any suitable analyzer that is capable of detecting etch products such as gaseous SiF<sub>x</sub> molecules in a gas stream. Residual Gas Analyzers (RGA's) are available from AMETEK, Anglo Scientific, Ferran Scientific, Hiden Analytical, VG Gas Analysis Systems and Stanford Research Systems. Depending upon the etch product, many gas analysis systems could be used, including UV and visible spectrometers, Raman Spectrometers, NRM Spectrometers, Mass Spectrometers, Infrared and Fourier Transform Infrared, or Atomic Spectrometers.

When gas outflow is impeded from the etching chamber as above, gas components monitored in a gas analyzer, particularly gaseous etching products, increase and then decrease. As can be seen in Fig. 5, etching products SiF<sub>3</sub>, SiF and SiF<sub>4</sub> increase in amount (ion current in a residual gas analyzer - RGA) up to a point around 2000 seconds, which is the end point of the reaction. After 2000 seconds, the etching product amounts that are detected in the RGA decrease. The increase in the initial curve is not found in a flow through system (as can be seen in Fig. 9) and the decrease at the end point is not found in pulse systems (as can be seen in Fig. 3 of the R. Toda reference mentioned above).

Taking SiF<sub>3</sub> as an example, as can be seen in Fig. 6A, the data from the RGA forms a rising then falling curve as also illustrated in Fig. 5. If these data are back averaged (e.g. with the previous 40 data points, a smoother curve results as shown in Fig. 6B. Because the average is an average with previously acquired data, this averaging can take place in real time. The new averaged data of Fig. 6B can be used to take a derivative (the rate of change of the etching product), which is the data shown in Fig. 7A. This data can also be back averaged (over 40 data points) to result in the curve shown in Fig.



7B. It is also possible to further process the curves of Fig. 6B and/or Fig. 7B with additional curve smoothing techniques as known in the art.

An accurate end point can be determined visually by a system operator monitoring the curves of one or more etching products on a computer monitor or print-out, or preferably, the end point is automatically determined based on the data from the gas analyzer. In a preferred embodiment, the end point is flagged (audio signal or visual alert). The end point can be determined in a number of ways. As can be seen in Fig. 6B, the RGA output increases and then decreases at a time around 2000 sec (2000 sec is arbitrary and depends upon the amount of sacrificial material being etched, the etchant concentration, process temperature and pressure, etc.). A software program can be used to look for a peak value from the gas analyzer (corresponding roughly to the datum at time 2000 sec.) or to look for a decrease (or average decrease over time) – also taking place at around 2000 sec. in the example in Fig. 6B. In one method of the invention, the end point is detected after the signal from the gas analyzer decreases for 3/4 of all data points in a 25 to 40 point range. In another way of determining the end point, the back-averaged data of Fig. 6B is again averaged over, e.g. 10 data points or more, consecutively along the curve, and when the average of any group of 10 (or more) data points is lower than the previous 10 point average, the end point is flagged.

As seen in Figs. 7A and 7B, the derivative of the data in Fig. 6B can be taken (Fig. 7A) and then back averaged (Fig. 7B). Because graph 7B indicates the rate of change of the data of the gas analyzer, similar to the discussion above with respect to Fig. 6B, when the rate of change passes across point 0 (again at time 2000 sec. in Fig. 7B) this indicates that the rate of change of the detected etch product is no longer increasing and is, in fact decreasing. Crossing from positive to negative values in Fig. 7B can be monitored and flagged as the end point of the etching reaction.

At the determined end point, if the method is being run in real time, in a preferred embodiment, the etch process is stopped – the bleeding of etchant into the expansion chamber (or etching chamber if there is no expansion chamber) is stopped, and any etchant and etch products are vented out of the etching chamber with an inert gas (e.g. N<sub>2</sub>, Ne or Ar). It is also possible, upon determination of the end point as above, to allow the etching reaction to proceed for a predetermined period of time T (e.g. 20 to 100 seconds), in order to allow for slight over-etching in the etch process. The stopping of the etch process upon end point determination can be made manually or automatically.

Sacrificial silicon layers that can be removed using the apparatus and method of this invention may be layers of crystalline silicon, amorphous silicon, partially crystalline silicon, crystalline silicon of multiple crystal sizes, polysilicon in general, and silicon doped with such dopants as arsenic, phosphorus or boron. Amorphous silicon and polysilicon are of particular interest, although the relative

crystalline vs. amorphous character of polysilicon will vary considerably with the deposition conditions, the presence or absence of dopants and impurities, and the degree of annealing.

Silicon can be preferentially removed relative to non-silicon materials by the method and apparatus of this invention. The term "non-silicon material" denotes any material that contains neither amorphous nor crystalline silicon in any of the forms described in the preceding paragraph. Non-silicon materials thus include silicon-containing compounds in which elemental silicon is bonded to another element, as well as non-silicon elements and compounds of non-silicon elements. Examples of such non-silicon materials are titanium, gold, tungsten, aluminum, and compounds of these metals, as well as silicon carbide, silicon nitride, photoresists, polyimides, and silicon oxides. Silicon nitride and silicon oxide are of particular interest in view of their use in the structures disclosed in United States Patent No. 5,835,256. Two or more different non-silicon materials may be present in a single structure, and selectivity of the silicon etch relative to all such non-silicon materials will be improved.

When the present invention is applied to the mirror structures disclosed in United States Patent No. 5,835,256, to remove silicon layers from those structures, the thickness and lateral dimensions of the layers may vary. The silicon portion will generally however be a layer having a thickness of from about 200 nm to about 5,000 nm, preferably from about 250 nm to about 3,000 nm, and most preferably from about 300 nm to about 1,000 nm, though of course any thickness of material can be etched as desired. Similarly, the non-silicon portion will generally be a layer with a thickness of from about 10 nm to about 500 nm, preferably from about 20 nm to about 200 nm, and most preferably from about 30 nm to about 200 nm, though many structural materials having different dimensions are possible. The lateral distance that the etching process must extend under the typical silicon nitride mirror element in the structures of United States Patent No. 5,835,256 in order to remove all of the underlying polysilicon (this distance typically being half the shortest lateral dimension of the mirror when the etching front travels inward from opposing edges) may range from a submicron distance to about 500 microns, preferably from about 3 microns to about 30 microns, and most preferably from about 5 microns to about 15 microns.

While much of the foregoing description is directed to applications of the present invention to etching processes, the invention, and particularly its recirculation aspect, is applicable in general to processes for adding or removing layers within a device, particularly layers that have microscopic dimensions. Examples of such processes are passivation and etching of semiconductor devices and MEMS (including MOEMS) devices, lithography (screen printing, for example), thin-film deposition (chemical vapor deposition e.g. application of self-assembled monolayers and sputtering, for example), electroplating (blanket and template-delimited electroplating of metals, for example), and directed

deposition (as used in electroplating, stereolithography, laser-driven chemical vapor deposition, screen printing, and transfer printing, for example). Further examples are plasma etching, reaction-ion enhanced etching, deep reactive ion etching, wet chemical etching, electron discharge machining, bonding (such as fusion bonding, anodic bonding, and the application of adhesives), surface  
 5 modification (such as wet chemical modification and plasma modification), and annealing (such as thermal or laser annealing). The process gases in each case will be readily apparent to those skilled in the respective arts. The present invention is also useful in processes where at least one of the components of the process gas is corrosive to metal in the presence of water vapor. Corrosive components can be used for adding or removing material in a microscopic device without picking up  
 10 impurities that will lower the product yield and that might damage the pump used in the recirculation loop.

Further variations within the scope of the present invention are as follows. The recirculation loop 36 of FIG. 2 can be expanded to include the source chamber(s) 11. A valve arrangement can be incorporated into the design that allows the operator to choose between placing the source chamber within the recirculation loop and isolating the source chamber from the recirculation loop. Similarly,  
 15 diluent gas can be added to the recirculation loop simultaneously with the process gas, and an appropriate valve arrangement can be incorporated that would provide the operator with the option to do so. Appropriate valve arrangements can also provide the option of extending the recirculation loop 36 through the etch chamber 15 only or through both the etch chamber 15 and the expansion chamber 12.

As also noted above, a filter 39 can be placed in the recirculation loop 36 to filter out at least one (and preferably all) of the byproducts or effluent produced by the reactions occurring in the etch chamber 15. This improvement may be applied to an etching or deposition process with or without energetically enhancing the process gas. A selective filter that allows the process gas to pass would be preferred. Of course, the filter can be a basic particulate filter as well. Again, these are only examples.  
 25 Other variations and modifications will be readily apparent to those skilled in the art. For example, the end point calculations can take into account not only the data from the gas analyzer, but also additional data if collected, such as data from previously run samples, change in sample weight, optical monitoring of the samples, etc. Use of neural networks for end point detection are disclosed in, for example, Liamanond, S., Si, J., Yean-Ling Tseng, "Production data based optimal etch time control design for a reactive ion etching", IEEE Trans. on Semic. Manufact., 2/99, vol 12, no.1, p. 139-47, where neural  
 30 networks are used to model the functional relationship between an end point detection signal from an RIE process, as well as various in situ measurements, and the resulting film thickness remaining.

Though the apparatus and process disclosed herein are for etching a material from any work piece (semiconductor device, MEMS device, device to be cleaned of silicon residue, etc.), in one embodiment the material being removed is a sacrificial layer in a MEMS fabrication process. A specific example of a MEMS device that could be made in accordance with the invention is a micromirror array such as disclosed in US patents 5,835,256 and 6,046,840 to Huibers et al. The method of making micromirrors could be that set forth in US patent application 09/767,632 to True et al., filed January 22, 2001 or 09/631,536 to Huibers et al. filed August 3, 2001. The MEMS device, of course, could be any device, including movable mirror elements for optical switching such as disclosed in US patent application 09/617,149 to Huibers et al. filed July 17, 2000. The materials that are not etched can be as described herein, or such as described in US patent application 09/910,537 to Reid filed July 20, 2001 or in US patent application 60/300,533 to Reid filed June 22, 2001. Each of the above patents and applications are incorporated herein by reference.

#### SELECTIVITY:

The improved selectivity in the present invention is related to an etch rate that is slower than in the prior art. In one embodiment of the invention, the etch rate is less than 30  $\mu\text{m/hr}$ , and preferably less than 27.7  $\mu\text{m/hr}$ . Slower etch rates can achieve better selectivity in the present invention, and etch rates as low as 10  $\mu\text{m/hr}$  or less, or even 7.2  $\mu\text{m/hr}$  or less can be performed for even greater improvements in selectivity. Though total process time is impacted, etch rates as low as 3  $\mu\text{m/hr}$  or less, 2  $\mu\text{m/hr}$  or less, or even 1  $\mu\text{m/hr}$  or less are within the scope of the invention. Of course within all ranges above, the etch rate is greater than 0.

Reducing the etch rate in the present invention can be achieved by altering one or more of the etch parameters known to effect etch rate (e.g. etchant concentration, pressure, temperature, etc.). It is not as important which parameter(s) is used to achieve the low etch rate as long as the etch depth per time is within the low ranges as set forth herein. Selectivity, depending upon the etch rate, can be 500:1 (relative to a "non silicon" material, such as a silicon compound – e.g. silicon nitride or silicon oxide), 1000:1, 2000:1 or even 10,000:1 or higher depending upon the etch rate and the non-silicon material.

The selectivity of the etch can be further improved by use of diluents with the gas phase chemical etchant. The etch selectivity is increased by using as the etching medium a gas mixture containing the etchant gas(es) and one or more of certain additional but non-etchant gaseous components. While the inclusion of non-etchant gaseous additives causes prolongation of the etch time, those additives whose molar-averaged formula weight is below that of nitrogen gas prolong the etch time to a much lesser extent than do those whose molar-averaged formula weight is equal to or

greater than that of molecular nitrogen, while still achieving the same improvement in selectivity. The improvement in selectivity is achievable independently of the partial pressure of the etchant gas in the gas mixture. Likewise, the limitation on the increase in etch time when the averaged formula weight of the additive gas is less than that of molecular nitrogen is achievable independently of the partial  
5 pressure of the etchant gas in the gas mixture. Both the increase in selectivity and the limitation on the etch time are sufficiently great that significant improvements in uniformity, yield, and product reliability are achieved.

These discoveries offer numerous advantages, for example in overetching, i.e., etching purposely done to a degree beyond that which is strictly required for removal of the sacrificial silicon.  
10 Since the high selectivity allows one to overetch without introducing nonuniformity across the mirror array, this invention permits the use of overetching as a convenient and effective means of assuring complete removal of the sacrificial silicon while still preserving the integrity of the mirror elements. The invention thus eases the requirement for precise end point detection, i.e., precise detection of the point at which the last of the sacrificial silicon is removed. Another advantage stems from the dilution effect of  
15 the additive gas. Dilution improves the circulation of the gaseous mixture through the system by adding to the mass that flows through the recirculation system or agitator when such pieces of equipment are present. Also, the presence of the additive gas helps reduce high local concentrations of the etchant at the sample surface. Each of these factors improves microstructure uniformity and yield.

This aspect of the invention is of particular interest in etching processes that are not performed  
20 in a plasma environment, i.e., etching processes performed without the use of externally imposed energy such as ultraviolet light or high frequency electromagnetic energy to excite the gases into a plasma state. The invention is also of particular interest in isotropic etching processes, notably those in which the silicon and the non-silicon portions (as defined below) of the microstructure are overlapping layers, coextensive or otherwise, or nonoverlapping layers, sharing a common boundary or separated  
25 but still simultaneously exposed to the etchant gas. The invention is particularly useful in structures in which the silicon is a layer positioned underneath a layer of the non-silicon material such that removal of the silicon by etching requires lateral access through vias in the non-silicon layer. The invention is also of particular interest in the manufacture of reflective spatial light modulators of the type described in United States Patent No. 5,835,256, in which the mirror elements are formed of silicon nitride or silicon  
30 dioxide and the underlying sacrificial layer serving as the support to be removed by etching is polysilicon.

As mentioned previously, etching processes addressed by this invention are those in which the etchant is one or more gaseous noble gas fluorides, one or more gaseous halogen fluorides, or

combinations of gaseous noble gas fluorides and halogen fluorides. The noble gases are helium, neon, argon, krypton, xenon and radon, and among these the preferred fluorides are fluorides of krypton and xenon, with xenon fluorides the most preferred. Common fluorides of these elements are krypton difluoride, xenon difluoride, xenon tetrafluoride, and xenon hexafluoride. The most commonly used noble gas fluoride in silicon etch procedures is xenon difluoride. Halogen fluorides include bromine fluoride, bromine trifluoride, bromine pentafluoride, chlorine fluoride, chlorine trifluoride, chlorine pentafluoride, iodine pentafluoride and iodine heptafluoride. Preferred among these are bromine trifluoride, bromine trichloride, and iodine pentafluoride, with bromine trifluoride and chlorine trifluoride the more preferred. Combinations of bromine trifluoride and xenon difluoride are also of interest.

The gas mixture is preferably contacted with the sample at a pressure below atmospheric pressure. The term "sample" is used herein to denote the article from which the sacrificial silicon is sought to be removed in a selective manner relative to other materials which may reside in separate layers or regions of the article. The "sample" may thus be a single mirror element and its associated layers of other materials, a test pattern, a die, a device, a wafer, a portion of a wafer, or any article containing sacrificial silicon. While the rate of the etching reaction may vary with the partial pressure of the etchant gas, the partial pressure is generally not critical to the invention and may vary. In most applications, best results will be obtained with the etchant gas at a partial pressure of at least about 0.1 mbar (0.075 torr), preferably at least about 0.3 mbar (0.225 torr), more preferably within the range of from about 0.3 mbar (0.225 torr) to about 30 mbar (22.5 torr), and most preferably from about 1 mbar (0.75 torr) to about 15 mbar (11.25 torr). These pressure ranges are particularly applicable to xenon difluoride.

The gaseous additive that is included in the gas mixture to increase the selectivity of the silicon etch is a gas that is not itself active as an etching agent, and preferably a non-halogen-containing gas. The additive may be a single species or a mixture of species. In preferred embodiments of this invention, the additives are those whose molar-averaged formula weight (expressed in daltons or grams per mole) is less than the formula weight of molecular nitrogen, preferably about 25 or less, still more preferably within the range of from about 4 to about 25, still more preferably within the range of from about 4 to about 20, and most preferably within the range of from about 4 to about 10. If a single additive species is used, the "molar-averaged formula weight" is the actual formula weight of that species, whereas if two or more additive species are used in the same gas mixture, the molar-averaged formula weight is the average of the formula weights of each species in the mixture (exclusive of the noble gas fluoride) calculated on the basis of the relative molar amounts (approximately equal to the partial pressures) of each species. In terms of thermal conductivity, preferred additives are those whose

thermal conductivity at 300 K (26.9°C) and atmospheric pressure ranges from about 10 mW/(m K) (i.e., milliwatts per meter per degree Kelvin) to about 200 mW/(m K), and most preferably from about 140 mW/(m K) to about 190 mW/(m K). In general, the higher the thermal conductivity of the additive, the greater the improvement in selectivity. Examples of additives suitable for use in this invention are

5 nitrogen (N<sub>2</sub>, formula weight: 28; thermal conductivity at 300 K: 26 mW/(m K)), argon (Ar, formula weight: 40; thermal conductivity at 300 K: 18 mW/(m K)), helium (He, formula weight: 4; thermal conductivity at 300 K: 160 mW/(m K)), neon (Ne, formula weight: 20; thermal conductivity at 300 K: 50 mW/(m K)), and mixtures of two or more of these gases. For embodiments in which the molar-averaged formula weight is below that of molecular nitrogen, the preferred additive gas is helium, neon,

10 mixtures of helium and neon, or mixtures of one or both with one or more of higher formula weight non-etchant gases such as nitrogen and argon. Particularly preferred additives are helium and mixtures of helium with either nitrogen or argon.

The degree of selectivity improvement may vary with molar ratio of the additive to the etchant gas, but this ratio is generally not critical to the utility of this invention. Here again, the molar ratio is

15 approximately equal to the ratio of the partial pressures, and in this case the term "molar ratio" denotes the ratio of the total number of moles of the additive gas (which may be more than one species) divided by the total number of moles of the etchant gas (which may also be more than one species). In most cases, best results will be obtained with a molar ratio of additive to etchant that is less than about 500:1, preferably within the range of from about 1:1 to about 500:1, preferably from about 10:1 to about 200:1,

20 and most preferably from about 20:1 to about 100:1.

The temperature at which the etch process is conducted is likewise not critical to this invention. The temperature does however affect the partial pressure of the etchant gas and the optimal temperature may depend on the choice of etchant gas, gaseous additive or both. In general, and particularly for procedures using xenon difluoride as the etchant gas, suitable temperatures will range

25 from about -60°C to about 120°C, preferably from about -20°C to about 80°C, and most preferably from about 0°C to about 60°C. For xenon difluoride, the silicon etch rate is inversely proportional to the temperature over the range of -230°C to 60°C. The improvement in selectivity can thus be further increased by lowering the etch process temperature.

The duration of the exposure of the sample to the gas mixture in the practice of this invention

30 will be the amount of time sufficient to remove all of the silicon or substantially all, i.e., any amount sufficient to permit the microstructure to function essentially as effectively as if all of the silicon had been removed. An advantage of the high selectivity achieved with this invention is that it permits overetching of the silicon without significant loss of the non-silicon material. The time required for the etching

process will vary with the amount of silicon to be removed and the dimensions and geometry of the silicon layer, and is not critical to this invention. In most cases, best results will be achieved with an exposure time lasting from about 30 seconds to about 30 minutes, preferably from about 1 minute to about 10 minutes. An example of the structures to which this invention will be applied is that depicted in United States Patent No. 5,835,256, in which a silicon nitride layer is deposited over a polysilicon layer, and the silicon nitride layer is patterned to leave vias that define the lateral edges of the mirror elements. Access to the sacrificial polysilicon layer is through the vias, and the etching process removes the polysilicon below the vias by etching in the vertical direction (i.e., normal to the planes of the layers) while also removing the polysilicon underneath the silicon nitride by etching in the lateral direction (parallel to the planes of the layers).

In certain procedures within the scope of this invention, the manner and the order in which the gases in the gas mixture are combined may have an effect on the quality of the finished product. Variations may thus be introduced in the order of combining the etchant gas with the non-etchant diluent or whether this is done in portions, or, when two or more non-etchant diluents are used, the decision to combine one diluent with the etchant gas before adding the other diluent, or which diluent or subcombination is the first to contact the sample. Such variations may affect parameters of the process such as the diffusion time, the reaction rate at the surface of the sample, and the rate of removal of reaction products from the surface.

The sacrificial silicon layers to which this invention is applicable may be crystalline silicon, amorphous silicon, partially crystalline silicon, crystalline silicon of multiple crystal sizes, polysilicon in general, and silicon doped with such dopants as arsenic, phosphorus or boron. Polysilicon is of particular interest, although the relative crystalline vs. amorphous character of polysilicon will vary considerably with the deposition conditions, the presence or absence of dopants and impurities, and the degree of annealing.

The term "non-silicon" as used herein denotes any material that does not contain either amorphous or crystalline silicon in any of the forms described in the preceding paragraph. The term thus includes silicon-containing compounds in which elemental silicon is bonded to another element, as well as non-silicon elements and compounds of non-silicon elements. Examples of such non-silicon materials are titanium, gold, tungsten, aluminum, and compounds of these metals, as well as silicon carbide, silicon nitride, and silicon oxides. Silicon nitride and silicon oxide are of particular interest in view of their use in the structures disclosed in United States Patent No. 5,835,256. Two or more different non-silicon materials may be present in a single structure, and selectivity of the silicon etch relative to all such non-silicon materials will be improved.



The thickness and lateral dimensions of the layers are also noncritical to the improvement in selectivity achieved by this invention. In most cases, the silicon portion will be a layer having a thickness of from about 200 nm to about 5,000 nm, preferably from about 250 nm to about 3,000 nm, and most preferably from about 300 nm to about 1,000 nm. Similarly, in most cases the non-silicon portion will be a layer with a thickness of from about 10 nm to about 500 nm, preferably from about 20 nm to about 200 nm, and most preferably from about 30 nm to about 200 nm. The lateral distance that the etching process must extend under the typical silicon nitride mirror element in the structures of United States Patent No. 5,835,256 in order to remove all of the underlying polysilicon (this distance typically being half the shortest lateral dimension of the mirror when the etching front travels inward from opposing edges) may range from a submicron distance to about 100 microns, preferably from about 3 microns to about 30 microns, and most preferably from about 5 microns to about 15 microns.

The sample being etched comprises a layered structure formed on a quartz plate measuring 11.3 mm × 15.6 mm. The first layer was a continuous polysilicon layer deposited directly on one side of the quartz, and the second layer was patterned silicon nitride deposited directly over the polysilicon layer. The polysilicon layer measured 9.2 mm × 12.3 mm in lateral dimensions and was centered on the quartz surface, thereby leaving border regions along all four sides, and had a thickness of 0.5 micron. The silicon nitride layer was 249 nm (0.249 micron) in thickness and was coextensive with the quartz plate, thereby extending over both the underlying polysilicon layer and the border regions where no polysilicon had been deposited. The silicon nitride layer was patterned to form an array of square mirrors measuring 12 microns on each side with each pair of adjacent mirrors separated by a via 0.8 micron in width to expose the underlying polysilicon. Measurements of the thickness of the silicon nitride layer to assess the selectivity of the polysilicon etch were performed at four locations in the border regions, close to the four corners of the quartz plate, these locations being spaced apart from the edge of the polysilicon layer by distances greater than 300 microns. This distance was chosen to assure, for purposes of uniformity, that the measurement locations experienced no temperature rise from the exothermic polysilicon etch reaction, since the thermally insulating nature of silicon nitride precluded any such temperature rise at locations beyond approximately 100 microns from the edge of the polysilicon layer.

The time required for full removal of the polysilicon layer was determined by visual observation, as indicated above. The thickness of the silicon nitride at the measurement locations was determined both before and after the polysilicon etching by a common industry method of thin-film measurement using the reflectance of the film (as used in the NanoSpec Thin Film Measurement System of Nanometrics, Inc., Sunnyvale, California, USA, and in the Advanced Thin Film Measurement Systems of

Filmetrics, Inc., San Diego, California, USA). Measurements were performed on two or three samples for each experiment, and the results averaged. The results are listed in the table below, which include as the first experiment a control run with xenon difluoride alone and no additive.

#### Experimental Results

Experiment No.	No. of Samples	Gas in 1 <sup>st</sup> Gas Source	Gas in 2 <sup>d</sup> Gas Source	Time Required for Removal of Polysilicon	Si <sub>3</sub> N <sub>4</sub> Thickness Loss (Initial Thickness 249 nm)
					During Polysilicon Removal
I	3	none	none	65 sec	11-13 nm
II	3	N <sub>2</sub>	N <sub>2</sub>	610 sec	2-3 nm
III	2	Ar	Ar	590 sec	2-3 nm
IV	2	He	He	250 sec	2-3 nm

With the etching of the underlying polysilicon layer in the lateral direction, the etching distance of the polysilicon was one-half the width of each mirror element, or  $0.5 \times 12$  microns = 6,000 nm. The results in the table indicate that the selectivity of the etch of polysilicon relative to silicon nitride rose from approximately 500:1 (6,000 nm:11 nm) with the xenon difluoride-only etch medium in Experiment I to approximately 2,000:1 (6,000 nm:3 nm) with the addition of each of the additive gases in Experiments II, III and IV, and that the increase in etch time of the polysilicon when the additive was helium (Experiment IV) was well under half the attendant increases when the additives were nitrogen and argon, both of which had formula weights exceeding 25. These diluents are but examples, and any diluent or combination of diluents can be used, though preferably as long as the etch rate is within the low etch rate ranges of the invention.

As can be seen from the above various etch rates can be used to remove the sacrificial layer, including an etch rate can be 27.7  $\mu\text{m/hr}$  (.5  $\mu\text{m}$  etched in 65 sec.) such as if no diluent is used, or lower (e.g. 25 or 20  $\mu\text{m/hr}$  or less). For example, an etch rate of 7.2  $\mu\text{m/hr}$  (.5  $\mu\text{m}$  etched in 250 sec.) can be achieved with a helium diluent. Even lower etch rates are achieved in an argon diluent or in a nitrogen diluent (.5  $\mu\text{m}$  etched in 590 or 610 sec = 3  $\mu\text{m/hr}$ ). Other diluents and mixtures of diluents can be used, though it is preferred that the etch rate be 10  $\mu\text{m/hr}$  or less, 3  $\mu\text{m/hr}$  or less, or even 2  $\mu\text{m/hr}$  or 1  $\mu\text{m/hr}$  or less.

In a further embodiment of the invention, a MEMS device is formed where a sacrificial layer (or layers) is deposited on a substrate. During or after deposition the sacrificial layer, the sacrificial material

is doped with a dopant. The doping can occur during deposition of the sacrificial material, such as feeding a dopant into the process gas during a chemical vapor deposition of the sacrificial material. Or, the sacrificial material can first be deposited, followed by implanting the sacrificial layer with the dopant (e.g. phosphorous, arsenic, boron or other semiconductor dopant). In a preferred embodiment of the invention, the sacrificial layer is silicon (e.g. amorphous silicon, polycrystalline silicon), the material that is not to be etched is a non-silicon material, such as a metal (Al, Ti, Au, etc.) or metal compound (e.g. a nitride of titanium, aluminum tantalum-silicon, tungsten or an oxide of aluminum, silicon, tantalum, titanium, etc. or a metal carbide), where the silicon sacrificial is doped with the dopant. The dopant can be any dopant (e.g. borane, arsine or phosphine), though preferably one that improves the selectivity of the etch. Possible dopants if the sacrificial material is silicon, include PH<sub>3</sub>, P<sub>2</sub>H<sub>5</sub>, B<sub>2</sub>H<sub>5</sub>, BCl<sub>3</sub>, etc. The dopant can be implanted in accordance with standard semiconductor manufacturing implanting methods, or mixed into the process gas while depositing the sacrificial material, e.g. in accordance with such doping methods used in making solar cells. Other doping methods (diffusion, etc.) could also be used. The dopant can be used to dope only a top portion of the sacrificial layer, or the dopant can be made to be present throughout the sacrificial material. Doping can be at 10<sup>10</sup> to 10<sup>18</sup> ions/cm<sup>3</sup>, such as around 10<sup>14</sup> ions/cm<sup>3</sup>. Implantation can be performed at an energy of 10 to 70 keV, preferably from 20 to 40 keV. Other implantation densities and energies could also be used.

In the present invention, the silicon can be polysilicon as set forth above, or amorphous silicon deposited by LPCVD or PECVD, or sputtering, or other materials and techniques as set forth in US patent application 09/617,149 to Huibers et al. filed July 17, 2000, US patent application 09/631,536 to Huibers et al. filed August 3, 2000, and 09/637,479 to Huibers filed August 11, 2000, each incorporated herein by reference. Other micromechanical structural materials and methods can be used other than those set forth above, such as those materials set forth in US application 60/293,092 to Patel et al. filed May 22, 2001, US application 60/254,043 to Patel et al. filed December 7, 2000, US application 09/910,537 to Reid filed July 20, 2001, and US application 60/300,533 to Reid filed June 22, 2001, each incorporated herein by reference.

The foregoing description and examples are offered primarily for purposes of illustration. It will be readily apparent to those skilled in the art that numerous modifications and variations beyond those described herein can be made while still falling within the spirit and scope of the invention.